EXPERIMENTAL EVIDENCE OF THE HIGH ROBUSTNESS OF CsK_2Sb MULTI-ALKALI CATHODE

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Abstract

CsK_2Sb is a multi-alkali cathode which can be driven by a green laser generated as SHG of a solid state laser. The quantum efficiency is as high as 10%. In this article, we demonstrated that the cathode has an enough robustness to generate a high brightness electron beam. We found that 1/e lifetime of the cathode was inversely proportional to the vacuum pressure. The normalized temporal life was $(4.72 \pm 0.08) \times 10^{-5}$ Pa.hour for 532 nm laser. The lifetime regarding to the extracted charge density was also inversely proportional to the vacuum pressure. The normalized charge life was $(1.19 \pm 0.03 \pm 0.04) \times 10^{-4}$Pa.C/mm^2.

INTRODUCTION

The photo-cathode is one of the most important device in advanced electron linear accelerators such as linear colliders, ILC [1], XFEL [2], and ERL [3]. In the linac, the electron beam performance is determined by the initial beam quality and the beam current is equal to that provided by the electron source. Photo-cathode electron gun can generate such high performance beam, e.g. low emittance, short pulse, spin polarization [4] [5] with a large operability. To provide such high performance beam with a required time structure and intensity, quantum efficiency (QE) of photoelectric effect (ratio of the numbers of laser photon and photo-electron) of the cathode should be high enough and should be maintained for a reasonable period, e.g. accelerator maintenance period. Otherwise, we need a huge power laser and/or frequent cathode replacement. The QE and the robustness are always practical issues for the photo cathode. For example, NEA (Negative Electron Affinity)- GaAs [4] has a high QE (more than 10% at 530 nm), but the cathode function is easily lost by residual gas molecules such as H_2O, O_2, etc. On the other hand, metal cathode (Cu, Mg, Pb and so on) is much robust, but QE is typically low ($10^{-4} \sim 10^{-5}$) and need UV light for the excitation. Therefore, they are not suitable to generate high current electron beam. Recently, CsK_2Sb multi-alkali photo cathode is paid attention for the high brightness beam generation. This cathode is formed by evaporation with Sb, K, and Cs. The high robustness is already demonstrated [6] and QE is as high as more than 10% at 532 nm [7]. According to these reasons, this cathode is suitable to generate a high brightness electron beam for Linac. In Hiroshima University, CsK_2Sb multi-alkali photo cathode is studied to establish the technique to develop the high performance cathode and understand the property of the cathode [8]. In this article, operational lifetime of CsK2Sb cathode was experimentally studied.

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EXPERIMENT

In this section, we explain the experimental setup. In Hiroshima University, a multi-alkali test chamber and a laser control system were developed. The test chamber is made from SUS and the inner surface was electrically polished. Ultra-high vacuum in order of 10^{-9} Pa is kept with a NEG pump and an ion pump. The cathode is evaporated on a $31{\times}31$ mm^2 substrate made of SUS 304 whose surface was finished with the electrical polishing. The substrate is attached to a ceramic heater for the heat cleaning and temperature control. The holder is electrically isolated from the ground and is biased with a DC voltage supply to measure the photo-electron current. The photo-current is measured as the current provided by the power supply. The evaporation head generates Cs, K, and Sb vapor symmetry to the substrate and the quartz thickness monitor [8] to monitor the amount of the evaporated metal on the substrate simultaneously. Laser light can be introduced through a view port to observe photo-electron emission. To monitor the vacuum environment, an extractor vacuum gauge and QMS (Quadruple Mass Spectrometer) are placed.

2D distribution of QE of the cathode was measured by a laser scanning system. The laser position is controlled in two directions transverse to the laser direction. Two lasers (532 nm and 405 nm) were used for the measurement. With this system, the temporal evolution of the QE distribution for 532 nm and 405 nm light was obtained. In the experiment, the data were obtained with the following sequence. The QE distributions were taken with 532 nm and 405 nm laser, respectively. The spatial step size was 3 mm in two directions. After the scan, 405 nm laser illuminated on a specific spot of the cathode continuously. This sequence is repeated every two hours. In this experiment, the extracted current density of the specific position is significant, but the current density of the other place is negligible. Observing the QE evolution of the other place, QE evolution regarding to time is obtained. By comparing the QE evolution of the specific position and the other position, the effect of the extracted current density on the cathode lifetime can be obtained. In the next section, the experimental result and the analysis are presented.

RESULTS AND DISCUSSION

As the cathode degradation process, we assumed two components. One is regarding to time (temporal lifetime) and another is regarding to the density of the extracted charge (charge lifetime). Assuming these two components, the QE (η) evolution can be described as

$$\eta(t) = \eta_0 \exp\left(-\frac{\rho}{\theta}\right) \exp\left(-\frac{t}{\tau}\right), \quad (1)$$

where η_0 is the initial QE, t is time, τ is the temporal life, ρ is the extracted charge density, θ is the charge life. In fact, θ and τ can be varied during the experiment, e.g. by vacuum pressure fluctuation. As we will see later, the cathode degradation process strongly depends on the vacuum pressure. To treat the variation of θ and τ during the experiment, we introduce vacuum pressure $P(t)$ as a function of time,

$$\eta(t) = \eta_0 \exp\left(-\frac{\int P(t)J(t)dt}{\alpha}\right) \exp\left(-\frac{\int P(t)dt}{\beta}\right), \quad (2)$$

where α and β are normalized charge life and normalized temporal life, respectively. The dimension of the life are $Pa.C/mm^2$ and $Pa.hour$. $J(t)$ is the current density.

If the extracted charge density is negligible and the vacuum pressure is varied during the experiment, Eq.2 can be rewritten as

$$\eta(t) = \eta_0 \exp\left(-\frac{\int P(t)dt}{\beta}\right), \quad (3)$$

Figure 1 shows the QE evolution of several points measured by 405 nm laser as a function of $\int P(t)dt$, i.e. integrated pressure. Each legend shows the evolution for

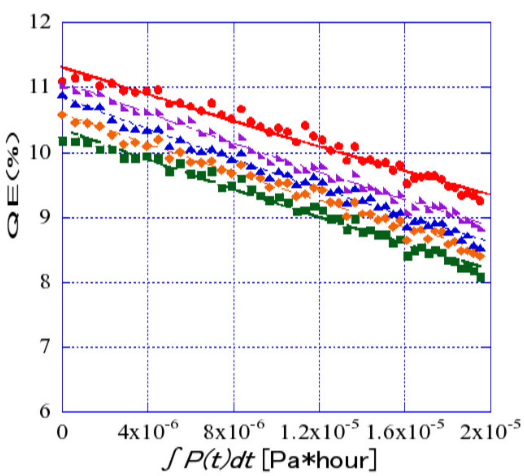

Figure 1: QE evolution as a function of the integrated vacuum pressure, Pa.hour.

different position on the cathode. The solid line shows the fitting curve by assuming Eq.1. The average of β over the cathode positions whose initial QE was more than 10% was $1.04 \pm 0.03\ 10^{-4}$(Pa.hour) for 405 nm laser and 4.72 ± 0.0810^{-5}(Pa.hour) for 532 nm laser. If we assume 1.0×10^{-8}Pa as a typical environment in accelerator, 1/e lifetime of the cathode is 10400 hours for 405 nm laser and 4720 hours for 432 nm. They are long enough for accelerator operation.

To investigate the vacuum pressure dependence of the temporal lifetime, we performed similar measurement at various vacuum pressure. The vacuum pressure were varied by heating the chamber and turning off the ion pump. The temporal lifetime τ in hour is shown as a function of the average vacuum pressure in Figure 2. Blue circle and green square show the data measured with 405 nm and 532 nm lasers, respectively. The solid and dashed lines are fitting curves assuming that τ is inversely proportional to the vacuum pressure. The data and lines show a good agreement to each other. This fact is consistent to that the cathode degradation regarding to time is caused by residual gas adsorption.

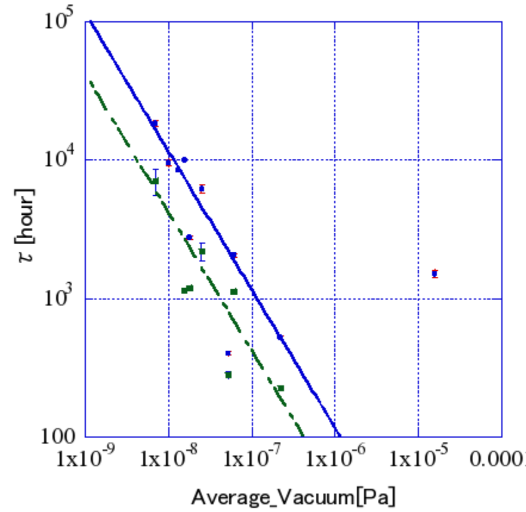

Figure 2: Temporal lifetime is plotted as a function of the average pressure. Blue circle and green square show the data with 405 nm and 532 nm lasers, respectively.

The charge density lifetime is obtained by measuring QE evolution as a function of the extracted charge density. A 405 nm laser was used to extract the beam current from the cathode with a large intensity. The laser power at the cathode was 400 mW, the spot size was 0.39mm^2 with 4σ in full-width, the typical beam intensity was 2.5mA/mm^2, and the average pressure during the experiment was 2.2×10^{-7}Pa. The high vacuum pressure comparing to the previous measurement was due to the large beam current hitting the vacuum chamber wall. The expected QE evolution for this measurement is expected to be as Eq.(2). The temporal contribution, the second term in Eq. (2) is not negligible. To extract the charge life, we have to correct the measured data with the temporal effect. Figure3 shows the QE evolution during the measurement with 532 nm laser. The horizontal axis is the integral of the product of the beam current density and the vacuum pressure. The blue circle shows the measured data. As expressed in Eq. 3, the measured degradation contains not only that by the charge density life effect, but also the temporal life effect. To extract only the charge density life

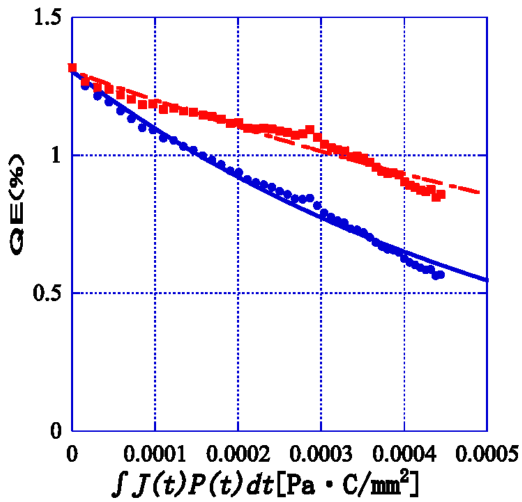

Figure 3: QE evolution as a function of the extracted charge density multiplied with the vacuum pressure is plotted. Blue circles and red squares are the measured data and the corrected data.

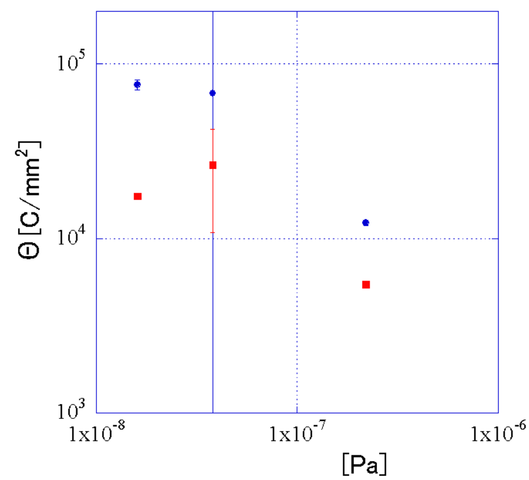

Figure 4: The charge density life (un-normalized) is plotted as a function of the average vacuum pressure. The blue circle and red square show the results taken with 405 nm and 532 nm lasers, respectively.

component, the data is corrected by the temporal life effect. The temporal life is estimated with a QE evolution of other cathode points where the laser illuminated not continuously. The red square points in Fig. 3 show the corrected data. The red dashed line is the fitting curve giving the charge density life as $\alpha = (1.19 \pm 0.03 \pm 0.04) \times 10^{-4}$ Pa.C/mm^2 for 532 nm laser, where the first error is due to the correction and the second error is statistic. By assuming 1.0×10^{-8} Pa, 1/e charge density life is expected to be 11900 C/mm^2. If 10 mA beam current is extracted from a tiny spot as $\phi 1$, 1/e life is 10.8 days. This number is acceptable as the operation period as the accelerator injector, because the typical maintenance period is two weeks.

The normalized charge density life α is principally independent on the vacuum pressure. By comparing several measurements in different vacuum pressure, we can confirm the speculation. Figure 4 shows the charge density life (un-normalized) as a function of the average vacuum pressure. We use the un-normalized life to demonstrate the vacuum pressure dependence. If the speculation is correct, the charge density life is inversely proportional to the average vacuum pressure. The results are consistent to the speculation.

To confirm our speculation further, we have observed the charge density life as a function of the bias voltage. The ionization cross section depends on the electron energy. If the bias voltage is changed, the number of generated ion by the electron beam is also changed through the cross section dependence. The charge density life α is inversely proportional to the cross section as

$$\alpha \propto \frac{1}{\int_0^d \sigma(E) ds}, \tag{4}$$

If we consider a simple one dimensional system between a cathode and an anode with a bias voltage, V, the total cross section is maximized around 100 V by assuming hydrogen as residual gas. Figure 5 shows the charge density life as a function of bias voltage. The blue circle and red square show the results taken with 405 nm and 532 nm lasers, respectively. The curves show the theoretical value by assuming hydrogen ionization. The experimental results are consistent to the theoretical expectation. This results show the charge density life is caused

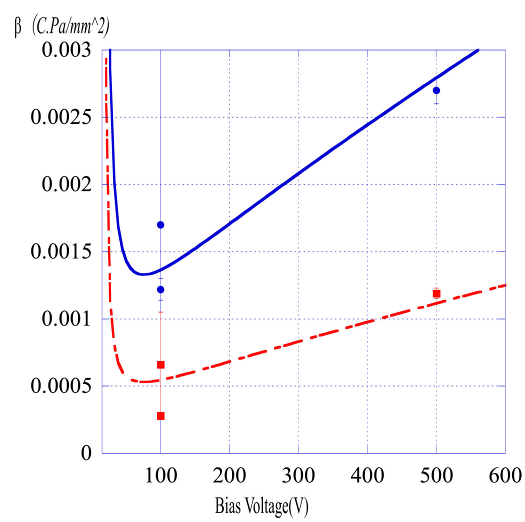

Figure 5: The charge density life is plotted as a function of the bias voltage. The blue circle and red square show the results taken with 405 nm and 532 nm lasers, respectively. The curves show the theoretical value by assuming hydrogen ionization.

CONCLUSION

Lifetime studies for CsK_2Sb cathode were carried out at Hiroshima University. By taking evlution of 2D distribution of cathode QE, the temporal life was obtained. We have confirmed that the temporal life is inversely proportional to the vacuum pressure. The normalized temporal life was $(1.04 \pm 0.03) \times 10^{-4}$ Pa.hour for 405 nm laser and $(4.72 \pm 0.08) \times 10^{-5}$ Pa.hour for 532 nm laser. By assuming 1.0×10^{-8} Pa, 1/e life is 10400 and 4720 hours for 405 and 532 nm lasers, respectively. The charge density life was obtained by measuring QE evolution with a large current extraction. The results are consistent to that the charge density life is inversely proportional to the vacuum pressure. The bias voltage dependence of the charge density life is also confirmed as it is consistent to the ion back bombardment hypothesis. The normalized charge density life was obtained as $(2.70 \pm 0.10 \pm 0.10) \times 10^{-3}$Pa.C/mm^2 and $(1.19 \pm 0.03 \pm 0.04) \times 10^{-4}$Pa.C/mm^2 for 405 and 532 nm lasers, respectively. By assuming 1.0×10^{-8}Pa, 1/e charge density life is 270000 and 11900 C/mm^2 for 405 and 532 nm lasers, respectively. These values are long enough for accelerator giving an reasonably long period for the operation.

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REFERENCES

[1] ILC Technical Design Report, KEK Report 2013, (2013).

[2] The Technical Design Report (TDR) of the European XFEL(2007).

[3] Design Study of Compact ERL, KEK-Report 2007-7 (2007).

[4] D.H. Dowell *et al.*, NIMA,622 ,pp685-697 (2010).

[5] I. Bazarov *et al.*, APL(98)224101(2011).

[6] B. Dunham *et al.*, APL(102)034105(2013).

[7] L. Guo *et al.*, PTEP(2017)0033G01.

[8] M. Kuriki *et al.*, in *Proc. Linac'16*, TUPLR013(2016).